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(54) Title: SYMBOL MAPPINGS FOR CODED MODULATIONS

(57) Abstract

One of the important considerations in a coded modulation scheme is the bits–to–symbol mapping, which has a significant impact on the overall error rate performance. Bits–to–symbol mappings are described that can achieve different levels of error protection for different classes of information and simultaneously optimize the performance of the different classes.

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SYMBOL MAPPINGS FOR CODED MODULATIONS

5   **BACKGROUND**

This invention relates to coded modulation schemes
and more particularly to bits-to-symbol mappings for such
schemes.

Coded modulations such as multi-level coding or
10   block coded modulation (BCM) can be used to increase the
information rate (spectral efficiency) of a communication
system without decreasing power efficiency. This increase
in the information rate is useful in a communication system
in which speech signals are digitized and compressed before
15   being transmitted. Higher compression saves bandwidth, but
reproduction quality suffers under adverse conditions in the
communication channel. The increased information rate with
coded modulation permits less compression to be used, and
hence reproduction quality can be improved. A greater
20   information rate, i.e., a greater information capacity, also
enables a communication system to accommodate more users.

Multi-level coding schemes, such as BCM, are
described in H. Imai et al., "A New Multi-Level Coding
Method Using Error Correcting Codes", IEEE Transactions on
25   Information Theory vol. IT-23, pp. 371-377 (May 1977); S.
Sayegh, "A Class of Optimum Block Codes in Signal Space",
IEEE Transactions on Communications vol. COM-34, pp. 1043-45
(Oct. 1986); A.R. Calderbank, "Multi-Level Codes and Multi-
Stage Decoding", IEEE Transactions on Communications vol.
30   COM-37, pp. 222-229 (Mar. 1989); G. Karam et al., "Block-
Coded Modulation Using Reed-Muller Component Codes with
Multistage Decoding", European Transactions on
Communications vol. 4, pp. 267-275 (May 1993); and T. Woerz
et al., "Decoding of M-PSK Multilevel Codes", European
35   Transactions on Communications vol. 4, pp. 299-308 (May
1993).

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Recent publications on the suitability of BCM for Rayleigh fading channels include N. Seshadri et al., "Multi-Level Coded Modulations for Fading Channels", Proceedings of the Fifth Tirennia International Workshop on Digital

5   Communications (E. Biglieri et al., eds.) pp. 341-352 (1992); N. Seshadri et al., "Coded Modulation with Time Diversity, Unequal Error Protection and Low Delay for the Rayleigh Fading Channel", Proceedings of First Universal Conference on Portable and Mobile Communications pp. 283-287

10   (Sept. 1992); and N. Seshadri et al., "Multi-Level Block Coded Modulations with Unequal Error Protection for the Rayleigh Fading Channel", European Transactions on Communication vol. 4, pp. 325-334 (May 1993). Multi-level BCM is an attractive scheme for combined modulation and

15   coding, particularly for Rayleigh fading environments where interleaving depth is a crucial factor in determining the bit error rate (BER) performance.

A transmitter using BCM and eight-point phase-shift keying (8-PSK) modulation is shown in Fig. 1, in which

20   a speech or other information source 11 generates a stream of digital data, such as binary bits, that passes to a speech encoder 13. The encoder 13, which may be a code-excited linear predictive coder, transforms the digital data into a plurality of streams $i_0, i_1, i_2, \ldots$ of encoded

25   digital data elements, each stream representing a respective subset of the information in the information data stream. In this 8-PSK example, there are three such streams i_0, i_1, i_2, although it will be understood that an M-ary modulation other than 8-PSK, such as 16-PSK or 16-ary quadrature

30   amplitude modulation (QAM), and other than three streams, i, of encoded digital data elements might be used. At least one of the streams of encoded data elements represents information in the speech signal that is more important than the information represented by the other streams.

35   The streams i_0, i_1, i_2 are provided as inputs to a BCM encoder 14, which includes a plurality of block encoders

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15 connected in parallel and a bits-to-symbol mapper 16.
The input streams are encoded according to respective block
codes C_0, C_1, C_2, yielding respective output streams of
codewords comprising respective streams b_0, b_1, b_2 of code

5   symbols, e.g., digital bits. The codes C are called
component codes, and have respective rates k/N, where N is
the block length and k is the number of input symbols that
are encoded in each block of N code symbols. This scheme
provides an overall information rate R = $(k_0 + k_1 + k_2)/(N)$

10 information bits per code symbol. For illustration, let the
code C_0 be the most powerful code, followed by the code C_1
and then the code C_2. With such an arrangement, the bit
stream i_0 would represent the most important class of
information, which may be called Class 0; the bit stream i_1

15 would represent the next most important class, which may be
called Class 1; and the bit stream i_2 would represent the
least important class, which may be called Class 2.
            Each of the succession of triplets of coded bits
$\{b_2 b_1 b_0\}$ produced by the block encoders 15 is used by the

20 mapper 16 to select a respective one of the constellation of
eight 8-PSK symbols according to a predetermined scheme. In
this example, b_2 is the most significant bit (MSB) and b_0 is
the least significant bit (LSB). A conventional bits-to-
symbol mapper uses either natural binary mapping or Gray

25 code mapping. In this way, three N-symbol block codewords
generated by the three block encoders 15 are transformed
into one modulation codeword, comprising N modulation
symbols.
            The bits-to-symbol mapper 16 produces a stream of

30 generally complex-valued (I + jQ) modulation symbols that is
provided to a symbol interleaver 17, which shuffles the
order of the modulation symbols, separating formerly
successive symbols in time. Interleaving helps spread the
effect of noise and other events in the physical

35 communication channel among the modulation symbols,
minimizing the chances that all of the symbols of a codeword

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will be affected and taking advantage of the built-in time
diversity of the multi-level block code. The stream of
interleaved modulation symbols produced by the symbol
interleaver 17 is provided to an I, Q modulator 18, which
5   quadrature modulates a carrier signal with those symbols.
The modulated carrier signal is transmitted via an antenna.

It will be understood that other components may be
included in the transmitter illustrated in Fig. 1. For
example, the data streams i may be scrambled before passing
10 to the encoder 14. Also, spectral shaping and amplification
may occur at various points. Since such functions are well
understood by those of skill in the art and are not
necessary to an understanding of Applicants' invention, a
description of them is not necessary here.

15   As described above, the BCM encoder 14 uses the
triplets {$b_2 b_1 b_0$} of coded bits as addresses for the 8-PSK
symbols, which may be stored in a memory at locations
identified by the addresses. The relationship between the
triplets and the modulation symbols is called a "mapping",
20 and typically either natural order binary mapping or Gray
code mapping is used. Fig. 2 illustrates a BCM encoder 14
in which C_0 is a (4,1) repetition code and C_1 and C_2 are
(4,3) single-parity-check codes, and Fig. 3 illustrates the
natural binary mapping of triplets to 8-PSK symbols. In the
25 encoder illustrated in Fig. 2, the block length N of the
codes C_0, C_1, C_2 is four, and thus four triplets of block
code symbols {111}, {100}, {110}, and {101} are used to
select four 8-PSK symbols that compose the BCM codeword
{$S_1 S_2 S_3 S_4$}. In this example of natural binary mapping, the
30 bits-to-symbol mapper 16 would transform code symbol
triplets to 8-PSK modulation symbols using the following
rule:

modulation symbol number = $4b_2 + 2b_1 + b_0$

where the eight 8-PSK modulation symbols, indicated in the
35 complex plane by the "x" marks, are consecutively numbered
counter clockwise starting from the positive real axis as

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shown in Fig. 3. The other conventional bits-to-symbol
mapping, Gray code mapping, is similarly depicted in Fig. 4.

U.S. Patent No. 5,289,501 to Seshadri et al.
describes a trellis coded modulation scheme and various
5   bits-to-symbol mappings. U.S. Patent No. 5,168,509 to
Nakamura et al. describes a multi-level QAM scheme and
various mappings, including natural binary mapping, Gray
code mapping, and "quadrant symmetry mapping".

From Figs. 3 and 4, it can be seen that for a
10   modulation symbol identified by the triplet $\{b_2'\ b_1'\ b_0'\}$,
there are four modulation symbols that differ in the bit b_0,
i.e., that are identified by triplets having $b_0 \neq b_0'$. The
probability of error in decoding that modulation symbol
(BER) depends on the minimum Euclidean distance between the
15   triplet $\{b_2'\ b_1'\ b_0'\}$ and the four triplets that have a
different b_0. From these observations, it can be determined
that the natural binary mapping offers the lowest
probability of error for bit b_2 and increasing probability
of error for bits b_1 and b_0, respectively. On the other
20   hand, the Gray code mapping offers the lowest probability of
error for bit b_0 and higher probability of error for bits b_1
and b_2. In general, the probability of error for one of the
bits can be reduced only at the expense of increasing the
probability of error for at least one of the other bits. In
25   a coded modulation scheme, the probability of bit error is
also affected by the choice of the component codes C_0, C_1,
and C_2.

One of the main features of block coded modulation
schemes is that each class of information is encoded
30   according to a respective code, and hence unequal error
protection of the classes can be readily achieved. The
unequal error protection is useful for applications such as
speech data, where all the bits are not equally important in
a perceptual sense. The optimization of a coded modulation
35   scheme involves choosing the component codes and the
appropriate bits-to-symbol mapping that achieve the desired

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performance specifications. For some component codes,
neither the natural mapping or Gray code mapping yields the
desired protection for the different classes.

5   In an application such as transmission of speech
data in the American Digital Cellular System, which is
specified by the IS-136 standard by the Telecommunications
Industry Association (TIA) and the Electronic Industries
Association (EIA), it is desirable for two classes of bits
to have a significantly better BER performance than
10   unencoded quadrature PSK (QPSK) and for one class of bits to
have the same or only slightly better BER performance than
unencoded QPSK. For this application, it has been found
that both natural binary mapping and Gray code mapping do
not provide adequate performance for the three classes of
15   information when using block coded modulation. For the BCM
scheme illustrated in Figs. 2 and 3, the natural binary
mapping results in the BER of all three classes of bits
being not appreciably different. Gray code mapping improves
the performance of the Class 0 information at the cost of
20   significant degradation of the other two classes. Since 6/7
of the information bits are represented by C_1 and C_2, this
scheme is inadequate in terms of performance.

          Moreover as noted above, natural binary mapping
and Gray code mapping are usually used for constellations of
25   modulation symbols that are uniformly spaced in the complex
plane, although some variations of the Gray code mapping
scheme for non-uniform constellations have been described.
Nevertheless, such schemes with non-uniform constellations
have practical and implementational disadvantages that make
30   these systems hard to use.

          A constellation of non-uniformly spaced modulation
symbols for improving the BER of certain classes of bits is
suggested in N. Seshadri et al., "Coded Modulation with Time
Diversity, Unequal Error Protection and Low Delay for the
35   Rayleigh Fading Channel", Proceedings of First Universal
Conference on Portable and Mobile Communications pp. 283-287

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(Sept. 29 - Oct. 2, 1992), which is cited above. This
scheme has the disadvantage that, since some modulation
symbols are closer together than when they are uniformly
spaced, this constellation is more susceptible to phase,
5   frequency, and timing-jitter errors. Phase errors arise
from phase noise in frequency synthesizers and
unsynchronized transmitter and receiver oscillators.
Frequency errors arise from Doppler shifts and
unsynchronized transmitter and receiver oscillators. Timing
10   jitter arises from unsynchronized transmitter and receiver
clocks.

          These errors are manifest as rotations of the
modulation symbol constellation in the complex plane, which
can cause closer-together symbols to fall into the decision
15   regions of their neighbors. This causes ambiguity that
seriously impairs a communication system's ability to
achieve timing, frequency, and phase synchronizations, which
are necessary before decoding can occur. In view of the
need for reliable synchronization, constellations of
20   uniformly spaced modulation symbols have been preferred.

SUMMARY

          One of the important considerations in a coded
modulation scheme is the bits-to-symbol mapping, which has a
25   significant impact on the overall error rate performance.
This application describes bits-to-symbol mappings that can
achieve different levels of error protection for different
classes of information and simultaneously optimize the
performance of the different classes.
30   In one aspect of Applicants' invention, a method
of coded modulation of information includes the steps of
encoding a stream of information bits according to a
predetermined code, thereby generating a stream of code
symbols, and mapping each code symbol onto a constellation
35   of modulation symbols, thereby generating a stream of
modulation symbols. The modulation symbols are assigned

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locations in the constellation based on maximizing the
product of non-zero squared Euclidean distances between code
symbols along decoding trellis paths.

Also, the modulation symbols may be assigned
5   locations in the constellation by minimizing a metric given
by:

$$M_{pd} = \sum_{i=1}^{N_p} \frac{N_i}{P_{di}}$$

where N_p is a number of paths having differing product
distances, P_{di} is the product distance of an i-th path, and
N_i is a number of paths having the same product distance as
10 the i-th path.

In another aspect of Applicants' invention, an
apparatus for coded modulation of information includes a
device for encoding a stream of information bits according
to a predetermined code, thereby generating a stream of code
15 symbols, and a device for mapping each code symbol onto a
constellation of modulation symbols and generating a stream
of modulation symbols. The modulation symbols are located
in the constellation based on maximized products of non-zero
squared Euclidean distances between code symbols along
20 decoding trellis paths. Also, the modulation symbols may be
assigned locations in the constellation by minimizing a
metric such as that given by the equation listed above.

In another aspect of Applicants' invention, a
method of coded modulation of information includes the steps
25 of encoding a plurality of streams of information elements,
thereby forming a plurality of respective streams of coded
bits; forming code symbols out of successive groups of the
coded bits, wherein each group includes coded bits from all
streams of coded bits; and mapping code symbols onto a
30 constellation of modulation symbols, thereby generating a
stream of modulation symbols, wherein the modulation symbols
are assigned locations in the constellation based on

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maximized products of non-zero squared Euclidean distances between code symbols along decoding trellis paths.

Also, the modulation symbols may be assigned locations in the constellation by minimizing a metric given by the equation listed above. Each stream of information elements may be encoded according to a respective code, and the modulation symbols may be assigned locations in the constellation based on an optimized error rate performance for at least one of the streams of code symbols. Moreover, each stream of information elements may represent speech information and be encoded according to a respective block code.

In another aspect of Applicants' invention, an apparatus for coded modulation of information includes a device for encoding a plurality of streams of information elements and forming a plurality of respective streams of coded bits; a device for forming code symbols out of successive groups of coded bits, wherein each group includes coded bits from all streams of coded bits; and a device for mapping code symbols onto a constellation of modulation symbols and generating a stream of modulation symbols, wherein the modulation symbols are assigned locations in the constellation based on maximized products of non-zero Euclidean distances between code symbols along decoding trellis paths.

Also, the modulation symbols may be assigned locations in the constellation by minimizing a metric given by the equation listed above. Each stream of information elements may be encoded according to a respective code, and the modulation symbols may be assigned locations in the constellation based on an optimized error rate performance for at least one of the streams of code symbols. Moreover, each stream of information elements may represent speech information and be encoded according to a respective block code.

In another aspect of Applicants' invention, a
method of coded modulation of information includes the steps
of encoding a stream of information bits according to a
predetermined code, thereby generating a stream of code
5   symbols, and mapping each code symbol onto a constellation
of modulation symbols, thereby generating a stream of
modulation symbols. The code symbols are mapped according
to a hybrid of a natural binary mapping and a Gray code
mapping. Moreover, the hybrid may comprise a combination of
10 two Gray code mappings that are rotated 45° with respect to
each other.

In another aspect of Applicants' invention, an
apparatus for coded modulation of information includes a
device for encoding a stream of information bits according
15 to a predetermined code, thereby generating a stream of code
symbols, and a device for mapping each code symbol onto a
constellation of modulation symbols and generating a stream
of modulation symbols. The code symbols are mapped
according to a hybrid of a natural binary mapping and a Gray
20 code mapping, and the hybrid may comprise a combination of
two Gray code mappings that are rotated 45° with respect to
each other.

In another aspect of Applicants' invention, a
method of coded modulation of information includes the steps
25 of encoding a plurality of streams of information elements,
thereby forming a plurality of respective streams of coded
bits; forming code symbols out of successive groups of coded
bits, wherein each group includes coded bits from all
streams of coded bits; and mapping code symbols onto a
30 constellation of modulation symbols, thereby generating a
stream of modulation symbols, wherein the code symbols are
mapped according to a hybrid of a natural binary mapping and
a Gray code mapping.

Also, each stream of information elements may be
35 encoded according to a respective code, and the modulation
symbols may be located in the constellation based on an

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optimized error rate performance for at least one of the
streams of code symbols. Each stream of information
elements may represent speech information and be encoded
according to a respective block code, and the hybrid may
5   comprise a combination of two Gray code mappings that are
rotated 45° with respect to each other.

In another aspect of Applicants' invention, an
apparatus for coded modulation of information includes a
device for encoding a plurality of streams of information
10   elements and forming a plurality of respective streams of
coded bits; a device for forming code symbols out of
successive groups of coded bits, wherein each group includes
coded bits from all streams of coded bits; and a device for
mapping code symbols onto a constellation of modulation
15   symbols and generating a stream of modulation symbols,
wherein the code symbols are mapped according to a hybrid of
a natural binary mapping and a Gray code mapping.

Also, each stream of information elements may be
encoded according to a respective code, and the modulation
20   symbols may be located in the constellation based on an
optimized error rate performance for at least one of the
streams of code symbols. Each stream of information
elements may represent speech information and be encoded
according to a respective block code, and the hybrid may
25   comprise a combination of two Gray code mappings that are
rotated 45° with respect to each other.

In another aspect of Applicants' invention, a
method of coded modulation of information, includes the
steps of encoding a stream of information bits according to
30   a predetermined code, thereby generating a stream of encoded
information bits, and combining the stream of encoded
information bits with a stream of unencoded information
bits, thereby generating a stream of code symbols. Each
code symbol is then mapped onto a constellation of
35   modulation symbols, thereby generating a stream of
modulation symbols. Code symbols whose unencoded

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information bit is equal to a first value are mapped onto a
first constellation of modulation symbols, and code symbols
whose unencoded information bit is equal to a second value
are mapped onto a second constellation of modulation
5   symbols.

Also, modulation symbols in each of the first and
second constellations may be assigned locations based on
natural binary mapping. Alternatively, modulation symbols
in each of the first and second constellations may be
10   assigned locations based on Gray mapping. In yet another
alternative embodiment, modulation symbols in each of the
first and second constellations may be assigned locations in
the respective first and second constellation based on
maximized products of non-zero squared Euclidean distances
15   between code symbols along decoding trellis paths.

In another aspect of Applicants' invention, an
apparatus for coded modulation of information includes a
device for encoding a stream of information bits according
to a predetermined code, thereby generating a stream of
20   encoded information bits; a device for combining the stream
of encoded information bits with a stream of unencoded
information bits, thereby generating a stream of code
symbols; and a device for mapping each code symbol onto a
constellation of modulation symbols, thereby generating a
25   stream of modulation symbols. Code symbols whose unencoded
information bit is equal to a first value are mapped onto a
first constellation of modulation symbols, and code symbols
whose unencoded information bit is equal to a second value
are mapped onto a second constellation of modulation
30   symbols.

Also, modulation symbols in each of the first and
second constellations may be assigned locations based on
natural binary mapping. Alternatively, modulation symbols
in each of the first and second constellations may be
35   assigned locations based on Gray mapping. In yet another
alternative, modulation symbols in each of the first and

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second constellations may be assigned locations in the
respective first and second constellation based on maximized
products of non-zero squared Euclidean distances between
code symbols along decoding trellis paths.

5

BRIEF DESCRIPTION OF THE DRAWINGS

The features and advantages of the invention will
be understood by reading this description in conjunction
with the drawings, in which:

10   Fig. 1 illustrates a transmitter that includes a
BCM encoder;

Fig. 2 illustrates a BCM encoder;

Fig. 3 illustrates a natural binary mapping scheme
for the BCM encoder of Fig. 2;

15   Fig. 4 illustrates a Gray code mapping scheme for
the BCM encoder of Fig. 2;

Fig. 5 illustrates a BCM code trellis;

Fig. 6 illustrates a bits-to-symbol mapping based
on product distances according to Applicants' invention; and

20   Figs. 7a, 7b, 7c illustrate a hybrid bits-to-
symbol mapping according to Applicants' invention.

DETAILED DESCRIPTION

As described above, natural binary mapping and
25   Gray code mapping may not yield the desired unequal error
protection for a particular choice of component codes in a
coded modulation scheme. Applicants have solved this
problem and describe bits-to-symbol mappings that yield the
ability to trade-off the performance between the different
30   classes of bits while simultaneously optimizing the
performance of each of the different information classes.
Applicants' mapping schemes are advantageously implemented
by an improved bits-to-symbol mapper 17' that would be used
with the other components of a communication system such as
35   that illustrated in Fig. 1, therefore a description of the
general operation of such a system need not be repeated

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here. It will be appreciated that such a device may be
implemented as hard-wired logic circuitry of an application-
specific integrated circuit (ASIC) or as an integrated
digital signal processor. Of course it will be understood
5   that an ASIC may include hard-wired logic circuitry that is
optimal for performing a required function, which is an
arrangement commonly selected when speed or another
performance parameter is more important than the versatility
of a programmable digital signal processor.
10   One bits-to-symbol mapper in accordance with
Applicants' invention would implement a bits-to-symbol
mapping that is based on maximizing the product of squared
Euclidean distances (product distance) between the desired
and an erroneous sequence of symbols that could be decoded
15   under adverse channel conditions. This product distance
based (PDB) mapping can be derived from consideration of a
trellis representation of the coded modulation. Fig. 5
shows a trellis representation of a BCM scheme (see Figs. 1
and 2) comprising three component codes C_0 (rate 1/4
20   repetition code), C_1 (rate 3/4 single-parity-check code),
and C_2 (rate 3/4 single-parity-check code) whose code
symbols are mapped onto an 8-PSK constellation.
            The trellis shown in Fig. 5 is a complete
graphical representation of the BCM scheme as will be
25   described below. The following description assumes that the
speech coder has three bit classes that correspond to the
bits' perceptual significance and that are protected by a
BCM scheme accordingly, and the following description is in
terms of 8-PSK. Nevertheless, it will be appreciated by
30   those of ordinary skill in this art that the invention is
not limited to this example. Applicants' invention is
generally applicable to M-ary modulation schemes, such as M-
ary PSK, for which the M modulation symbols would be
addressed by M-tuples $\{b_{M-1}b_{M-2} \ldots b_1b_0\}$ that may be
35   derived from one or more information streams. The invention
is also generally applicable to coding schemes other than

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block coding and to speech coders having other than three
classes, and to other information sources.

Each possible BCM codeword corresponds to a
respective path through the trellis illustrated in Fig. 5.
5   In this example, the BCM component codes each have a block
length of four, yielding four triplets of code symbols
(addressing four 8-PSK symbols) for each BCM codeword that
represents seven information bits. The number of
information bits represented by each BCM codeword determines
10   the number of BCM codewords that can possibly occur in that
BCM code. In this example and since each information symbol
can take only one of two values (0 and 1), the number of
possible BCM codewords is $2^7 = 128$.

It can be seen that each path through the trellis,
15   e.g., the path ABCDO, comprises a set of branches, e.g., AB,
BC, CD, and DO. Each branch is labeled with the decimal
value of a respective triplet $\{b_2b_1b_0\}$ that can be generated
by the three component-code encoders 15 at each signalling
interval. For example, the branches AB, BC, CD, and DO are
20   labeled with the values 0, 0, 0, and 0, respectively. Thus
in this example, the path ABCDO represents the BCM codeword
comprising all zeroes, which is the result of mapping each
of a sequence of four triplets {000} onto a particular
constellation of modulation symbols. As another example,
25   the path ATPZO represents the BCM codeword comprising all
sevens.

Decoding such a BCM codeword may be done using a
maximum-likelihood technique like the well known Viterbi
algorithm, which has also been modeled as a trellis.
30   According to the Viterbi algorithm, each branch of the
trellis represents a symbol and a metric is assigned to each
branch that corresponds to the likelihood that the symbol
represented by that branch is the actual transmitted symbol.
One such metric is the squared Euclidean distance between a
35   received signal and an estimated value of the signal, using
the hypothesis that the symbol corresponding to that branch

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was actually transmitted.. Branches merge at each node in
the trellis, and at each node the branch assigned the lowest
valued metric is selected and used to update a node metric,
or path metric. This is repeated through the trellis, and
5   finally the path having the best path metric is selected.
The information bits that are represented by the symbols
represented by the selected path are produced as the decoded
bits.

The product distance is defined as the product of
10 the non-zero squared Euclidean distances of the symbols on
an erroneous path through the trellis relative to the
symbols on the correct path. The BER of such a coded
modulation scheme depends, to a first approximation, on the
product distance and the number of shortest error event
15. paths. The shortest error event path, which is inversely
proportional to the product distance along the error event,
is a path that diverges from the correct path and re-merges
with the correct path sooner than any other erroneous path.
In accordance with one aspect of Applicants' invention, a
20 bits-to-symbol mapping is chosen that maximizes the product
distance, thereby minimizing the BER (optimizing the BER
performance) for the corresponding class of information.
Hence, this mapping scheme is called PDB bits-to-symbol
mapping, which is illustrated by Fig. 6 for the exemplary
25 BCM scheme.

To a first approximation and for a given signal to
noise ratio, the BER can be minimized by minimizing the
metric M_{pd} given by the following expression:

$$M_{pd}=\sum_{i=1}^{N_p} \frac{N_i}{P_{di}}$$

where N_p is the number of paths of differing product
30 distances, P_{di} is the product distance of the i-th path, and
N_i is the number of paths with the same product distance as
the i-th path. Applicants' PDB mapping assigns symbols to

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the trellis branches such that the metric M_{pd} is minimized for each bit in the triplet $\{b_2 b_1 b_0\}$ identifying a modulation symbol. It will be appreciated, however, that the preceding expression for the metric M_{pd} is only one

5   possible rule for assigning modulation symbols to trellis branches; there may be other rules that yield comparable performance. For example, $N_p=1$, $M_{pd}=N_1/P_{d1}$ could be used as a first order approximation based on the shortest error event. The shortest error event is most likely to occur,

10   and is therefore a good rule to base the mapping on.

         Referring again to the example trellis shown in Fig. 5, assume the sequence of modulation symbols S_0, S_0, S_0, S_0 is transmitted, corresponding to the triplet sequence $\{000\}$ $\{000\}$ $\{000\}$ $\{000\}$. The corresponding (correct) path

15   in the trellis is ABCDO. Considering the performance of bit b_1, the paths ABIDO, ABJDO, AFCDO, AGCDO, ABCLO and ABCMO differ in only two branches from the correct path and give rise to an error in the bit b_1. These are the shortest error event paths for bit b_1. The corresponding product

20   distance on these branches is either
$P_{d1} = | S_0 - S_4 |^2 | S_0 - S_4 |^2$ (for paths ABIDO, AFCDO, and ABCLO) or $P_{d2} = | S_0 - S_6 |^2 | S_0 - S_6 |^2$ (for paths ABJDO, AGCDO, and ABCMO).

         For natural binary mapping (Fig. 3), $P_{d1} = 16$,

25    $P_{d2} = 4$, and $M_{pd} = 0.9375$. For Gray code mapping (Fig. 4), the product distances are $P_{d1} = 11.65$, $P_{d2} = 4$, and $M_{pd} = 1.0075$. For Applicants' PDB mapping (Fig. 6), the product distances are $P_{d1} = 16$, $P_{d2} = 11.65$, and $M_{pd} = 0.4450$. It can be seen that for bit b_2 Applicants'

30   PDB mapping minimizes M_{pd} and hence minimizes the BER for that bit. This has been confirmed by a computer simulation of a system using Applicants' PDB mapping.

         The performance of bits b_0 and b_1 can be similarly optimized, but it must be noted that improving the BER

35   performance of one class usually occurs at the expense of a decrease in performance of another class. The performances

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of the classes can be traded-off in different ways, depending on the application.

For speech transmission in the American Digital Cellular system specified by the IS-136 standard, in which

5   there are primarily two classes of information, Applicants' PDB mapping offers a better trade-off than Gray code mapping or natural binary mapping for the same coded modulation scheme. Natural binary mapping resulted in the BER of all three classes being not appreciably different. Gray code

10   mapping improved the performance of 1/7 of the bits at the cost of degrading the performance of the other 6/7 of the bits to a level worse than that of natural binary mapping. PDB mapping resulted in 4/7 of the bits having better performance and 3/7 of the bits having worse performance

15   relative to natural binary mapping.

In accordance with another aspect of Applicants' invention, a hybrid of natural binary mapping and Gray code mapping that can be used instead of PDB mapping is described below. This hybrid mapping is illustrated in Fig. 7a, from

20   which it can be seen that the hybrid mapping comprises a combination of two Gray code mappings of a constellation of four modulation symbols (4-PSK) that are illustrated in Figs. 7b, 7c. The two mappings shown in Figs. 7b and 7c are rotated by 45 degrees with respect to each other, and each

25   modulation symbol is identified by a doublet $\{b_2b_1\}$. These two constellations are superposed (yielding Fig. 7a) and distinguished by the third bit b_0, which together with the doublet $\{b_2b_1\}$ forms the triplet $\{b_2b_1b_0\}$ that identifies each 8-PSK symbol. The most heavily protected bit is mapped

30   onto bit b_0; the least protected is mapped onto bit b_2; and the remaining bit is mapped onto bit b_1. In effect, the hybrid mapping of Fig. 7a is formed by using the third bit b_0 for selecting between the two mappings of Figs. 7b, 7c. The bit b_0 has the least Euclidean distance between a given

35   modulation symbol and the other modulation symbols that

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differ in the bit b_0, just as in the case of natural binary
mapping.

     The hybrid mapping allows a favorable trade-off
between the performance of the different classes and yields

5   better overall performance than the conventional natural
binary mapping. Applicants' hybrid mapping, like the PDB
mapping, is useful applications such as speech transmission
in the American Digital Cellular System specified by the
IS-136 standard. Hybrid mapping currently appears to be

10   particularly useful for BCM schemes having one bit that is
unencoded, such as BCM schemes having component code rates
of [1/4, 3/4, 4/4] or [1/8, 6/8, 8/8] or [1/5, 4/5, 5/5].
The usefulness of such a BCM scheme lies in the fact that,
with one unencoded bit, the overall information rate is

15   increased, thereby allowing higher spectral efficiency.

     It will be appreciated that Applicants' PDB
mapping and hybrid mapping can be applied to other
convolutional coding, trellis coding and block coding
schemes by applying the principles of mapping bits such that

20   the code distance properties in combination with the
modulation symbol constellation are optimized. For example,
a serial stream of bits may be split into two parallel
streams, one of which may be encoded according to a rate 1/2
convolutional code and the other of which may remain

25   unencoded. The resulting bit triplets can be mapped onto an
8-PSK symbol constellation, e.g., by Applicants' hybrid
mapping. For another example, the serial stream may be
split into three information streams that are respectively
encoded according to three different convolutional codes

30   having rate 1/4, rate 3/4, and rate 3/4, respectively. The
encoded bits can be mapped onto an 8-PSK constellation using
one of the mappings described above, e.g., PDB mapping.

     It will be appreciated by those of ordinary skill
in the art that this invention can be embodied in other

35   specific forms without departing from its essence. The
embodiments described above are therefore to be considered

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illustrative and not restrictive. The scope of the
invention is defined by the following claims rather than the
foregoing description, and all changes that come within the
meaning and range of equivalents of the claims are intended
5 to be embraced therein.

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WHAT IS CLAIMED IS:

1.   A method of coded modulation of information,
comprising the steps of:
5   encoding a stream of information bits according to
a predetermined code, thereby generating a stream of code
symbols; and
             mapping each code symbol onto a constellation of
modulation symbols, thereby generating a stream of
10   modulation symbols,
             wherein the modulation symbols are assigned
locations in the constellation based on maximized products
of non-zero squared Euclidean distances between code symbols
along decoding trellis paths.
15

2.   The method of claim 1, wherein the modulation
symbols are assigned locations in the constellation by
minimizing a metric given by:

$$M_{pd} = \sum_{i=1}^{N_p} \frac{N_i}{P_{di}}$$

20   where N_p is a number of decoding trellis paths having
differing product distances, P_{di} is the product distance of
an i-th decoding trellis path relative to a desired decoding
trellis path, and N_i is a number of decoding trellis paths
having the same product distance as the i-th decoding
25   trellis path.

3.   An apparatus for coded modulation of information,
comprising:
             means for encoding a stream of information bits
30   according to a predetermined code, thereby generating a
stream of code symbols; and

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means for mapping each code symbol onto a
constellation of modulation symbols and generating a stream
of modulation symbols,

wherein the modulation symbols are located in the

5 constellation based on maximized products of non-zero
squared Euclidean distances between code symbols along
decoding trellis paths.

4.   The apparatus of claim 3, wherein the modulation
10 symbols are assigned locations in the constellation by
minimizing a metric given by:

$$M_{pd} = \sum_{i=1}^{N_p} \frac{N_i}{P_{di}}$$

where N_p is a number of decoding trellis paths having
differing product distances, P_{di} is the product distance of
15 an i-th decoding trellis path relative to a desired decoding
trellis path, and N_i is a number of decoding trellis paths
having the same product distance as the i-th decoding
trellis path.

20 5.   A method of coded modulation of information,
comprising the steps of:
encoding a plurality of streams of information
elements, thereby forming a plurality of respective streams
of coded bits, wherein each stream of information elements
25 is encoded according to a respective code;
forming code symbols out of successive groups of
coded bits, wherein each group includes coded bits from all
streams of coded bits; and
mapping code symbols onto a constellation of
30 modulation symbols, thereby generating a stream of
modulation symbols, wherein the modulation symbols are
assigned locations in the constellation based on maximized

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products of non-zero squared Euclidean distances between
code symbols along decoding trellis paths.

6.   The method of claim 5, wherein the modulation
5   symbols are assigned locations in the constellation by
minimizing a metric given by:

$$M_{pd} = \sum_{i=1}^{N_p} \frac{N_i}{P_{di}}$$

where N_p is a number of decoding trellis paths having
differing product distances, P_{di} is the product distance of
10   an i-th decoding trellis path relative to a desired decoding
trellis path, and N_i is a number of decoding trellis paths
having the same product distance as the i-th decoding
trellis path.

15   7.   The method of claim 5, wherein each stream of
information elements is encoded according to a respective
code, and the modulation symbols are assigned locations in
the constellation based on an optimized error rate
performance for at least one of the streams of code symbols.
20

8.   The method of claim 5, wherein each stream of
information elements represents speech information and is
encoded according to a respective block code.

25   9.   An apparatus for coded modulation of information,
comprising:
         means for encoding a plurality of streams of
information elements and forming a plurality of respective
streams of coded bits, wherein each stream of information
30   elements is encoded according to a respective code;

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means for forming code symbols out of successive groups of coded bits, wherein each group includes coded bits from all of the streams of coded bits; and

means for mapping code symbols onto a
5   constellation of modulation symbols and generating a stream of modulation symbols, wherein the modulation symbols are assigned locations in the constellation based on maximized products of non-zero Euclidean distances between code symbols along decoding trellis paths.
10

10.   The apparatus of claim 9, wherein the modulation symbols are assigned locations in the constellation by minimizing a metric given by:

$$M_{pd} = \sum_{i=1}^{N_p} \frac{N_i}{P_{di}}$$

15   where N_p is a number of decoding trellis paths having differing product distances, P_{di} is the product distance of an i-th decoding trellis path, and N_i is a number of decoding trellis paths having the same product distance as the i-th decoding trellis path.
20

11.   The apparatus of claim 9, wherein each stream of information elements is encoded according to a respective code, and the modulation symbols are assigned locations in the constellation based on an optimized error rate
25   performance for at least one of the streams of code symbols.

12.   The apparatus of claim 9, wherein each stream of information elements represents speech information and is encoded according to a respective block code.
30

13.   A method of coded modulation of information, comprising the steps of:

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encoding a stream of information bits according to
a predetermined code, thereby generating a stream of code
symbols; and

mapping each code symbol onto a constellation of
5   modulation symbols, thereby generating a stream of
modulation symbols,

wherein the code symbols are mapped according to a
hybrid of a natural binary mapping and a Gray code mapping.

10   14.   The method of claim 13, wherein the hybrid
comprises a combination of two Gray code mappings that are
rotated 45° with respect to each other.

15.   An apparatus for coded modulation of information,
15   comprising:

means for encoding a stream of information bits
according to a predetermined code, thereby generating a
stream of code symbols; and

means for mapping each code symbol onto a
20   constellation of modulation symbols and generating a stream
of modulation symbols,

wherein the code symbols are mapped according to a
hybrid of a natural binary mapping and a Gray code mapping.

25   16.   The apparatus of claim 15, wherein the hybrid
comprises a combination of two Gray code mappings that are
rotated 45° with respect to each other.

17.   A method of coded modulation of information,
30   comprising the steps of:

encoding a plurality of streams of information
elements, thereby forming a plurality of respective streams
of coded bits, wherein each stream of information elements
is encoded according to a respective code;

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forming code symbols out of successive groups of
the coded bits, wherein each group includes coded bits from
all of the streams of coded bits; and

mapping the code symbols onto a constellation of
5   modulation symbols, thereby generating a stream of
modulation symbols, wherein the code symbols are mapped
according to a hybrid of a natural binary mapping and a Gray
code mapping.

10   18.   The method of claim 17, wherein each stream of
information elements is encoded according to a respective
code, and the modulation symbols are located in the
constellation based on an optimized error rate performance
for at least one of the streams of code symbols.
15

19.   The method of claim 17, wherein each stream of
information elements represents speech information and is
encoded according to a respective block code.

20   20.   The method of claim 17, wherein the hybrid
comprises a combination of two Gray code mappings that are
rotated 45° with respect to each other.

21.   An apparatus for coded modulation of information,
25   comprising:
means for encoding a plurality of streams of
information elements and forming a plurality of respective
streams of coded bits, wherein each stream of information
elements is encoded according to a respective code;
30   means for forming code symbols out of successive
groups of the coded bits, wherein each group includes coded
bits from all of the streams of coded bits; and
means for mapping code symbols onto a
constellation of modulation symbols and generating a stream
35   of modulation symbols, wherein the code symbols are mapped

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according to a hybrid of a natural binary mapping and a Gray
code mapping.

22.   The apparatus of claim 21, wherein each stream of
information elements is encoded according to a respective
code, and the modulation symbols are located in the
constellation based on an optimized error rate performance
for at least one of the streams of code symbols.

23.   The apparatus of claim 21, wherein each stream of
information elements represents speech information and is
encoded according to a respective block code.

24.   The apparatus of claim 21, wherein the hybrid
comprises a combination of two Gray code mappings that are
rotated 45° with respect to each other.

25.   A method of coded modulation of information,
comprising the steps of:
          encoding a stream of information bits according to
a predetermined code, thereby generating a stream of encoded
information bits;
          combining the stream of encoded information bits
with a stream of unencoded information bits, thereby
generating a stream of code symbols; and
          mapping each code symbol onto a constellation of
modulation symbols, thereby generating a stream of
modulation symbols,
          wherein code symbols whose unencoded information
bit is equal to a first value are mapped onto a first
constellation of modulation symbols, and code symbols whose
unencoded information bit is equal to a second value are
mapped onto a second constellation of modulation symbols.

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26.   The method of claim 25, wherein modulation symbols in each of the first and second constellations are assigned locations based on natural binary mapping.

5   27.   The method of claim 25, wherein modulation symbols in each of the first and second constellations are assigned locations based on Gray mapping.

28.   The method of claim 25, wherein modulation symbols
10   in each of the first and second constellations are assigned locations in the respective first and second constellation based on maximized products of non-zero squared Euclidean distances between code symbols along decoding trellis paths.

15   29.   An apparatus for coded modulation of information, comprising:
        means for encoding a stream of information bits according to a predetermined code, thereby generating a stream of encoded information bits;
20   means for combining the stream of encoded information bits with a stream of unencoded information bits, thereby generating a stream of code symbols; and
        means for mapping each code symbol onto a constellation of modulation symbols, thereby generating a
25   stream of modulation symbols,
        wherein code symbols whose unencoded information bit is equal to a first value are mapped onto a first constellation of modulation symbols, and code symbols whose unencoded information bit is equal to a second value are
30   mapped onto a second constellation of modulation symbols.

30.   The apparatus of claim 29, wherein modulation symbols in each of the first and second constellations are assigned locations based on natural binary mapping.

35

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31.   The apparatus of claim 29, wherein modulation symbols in each of the first and second constellations are assigned locations based on Gray mapping.

5   32.   The apparatus of claim 29, wherein modulation symbols in each of the first and second constellations are assigned locations in the respective first and second constellation based on maximized products of non-zero squared Euclidean distances between code symbols along
10   decoding trellis paths.

Fig. 1

SOURCE 11

SPEECH ENCODER 13

Encoder C_0 Encoder C_1 Encoder C_2 15

i_0 i_1 i_2

b_0 b_1 b_2

BITS-to-SYMBOL MAPPER 14

Symbol Interleaver 17

I.Q Modulator 18

16

Fig. 2

i_0 1 → (4,1) REPETITION CODE → b_0

i_1 101 → (4,3) SINGLE PARITY CHECK CODE → b_1

i_2 100 → (4,3) SINGLE PARITY CHECK CODE → b_2

15

N=4 SIGNALLING INTERVAL

b_0 1 1 1 1
b_1 1 0 1 0
b_2 1 0 0 1

S_1 S_2 S_3 S_4 S_5 S_6 S_7 S_8

M CODEWORDS

Fig. 3

Fig. 4

Fig. 5

Fig. 6

101
111 ×   × 010
100 ×   × 000
                   $b_2 b_1 b_0$
110 ×   × 011
     001

Fig. 7c

01
×
11 ×   × 00
              $b_2 b_1$
×
10

Fig. 7b

01 ×   × 00
11 ×   × 10
              $b_2 b_1$

Fig. 7a

010
011 ×   × 001
110 ×   × 000
                 $b_2 b_1 b_0$
111 ×   × 101
     100
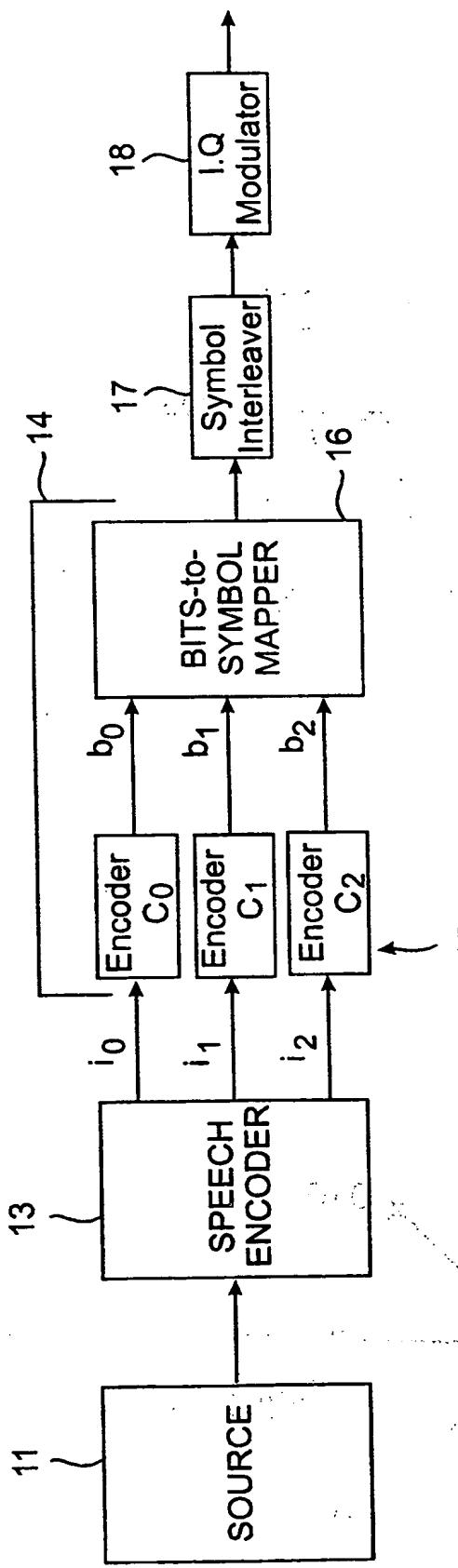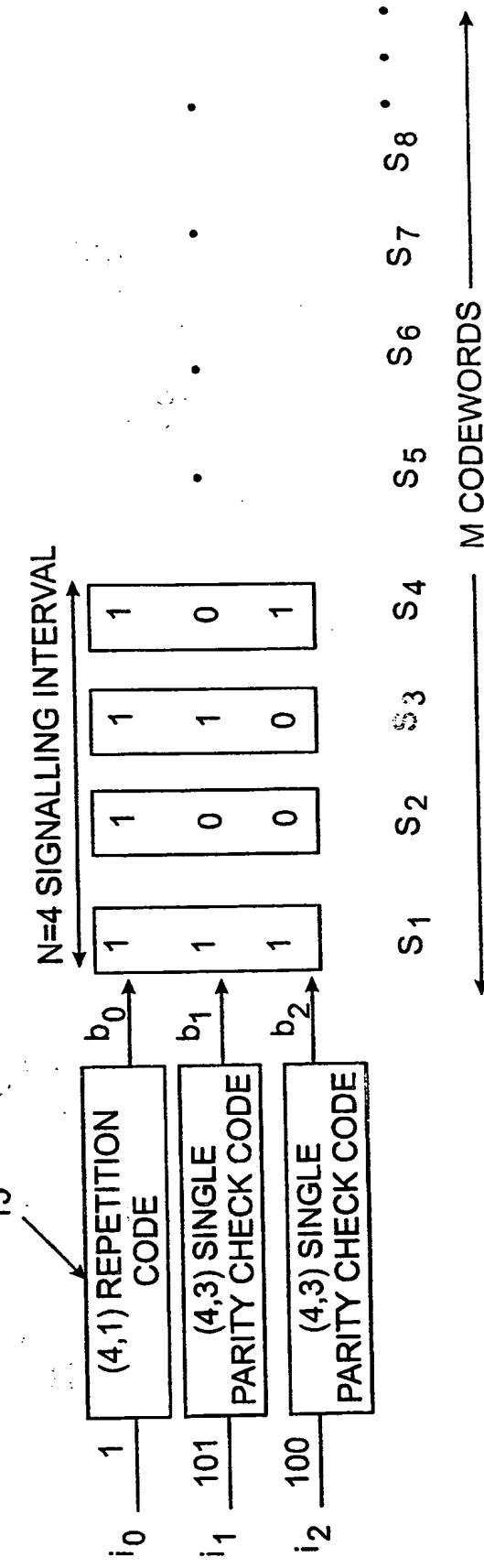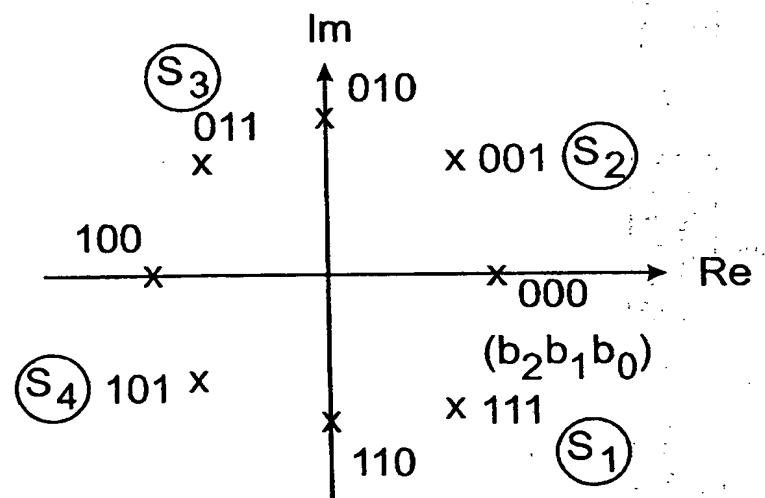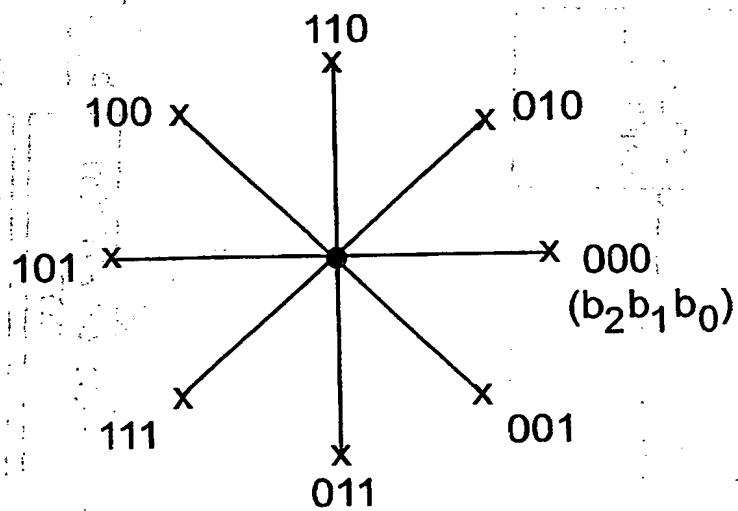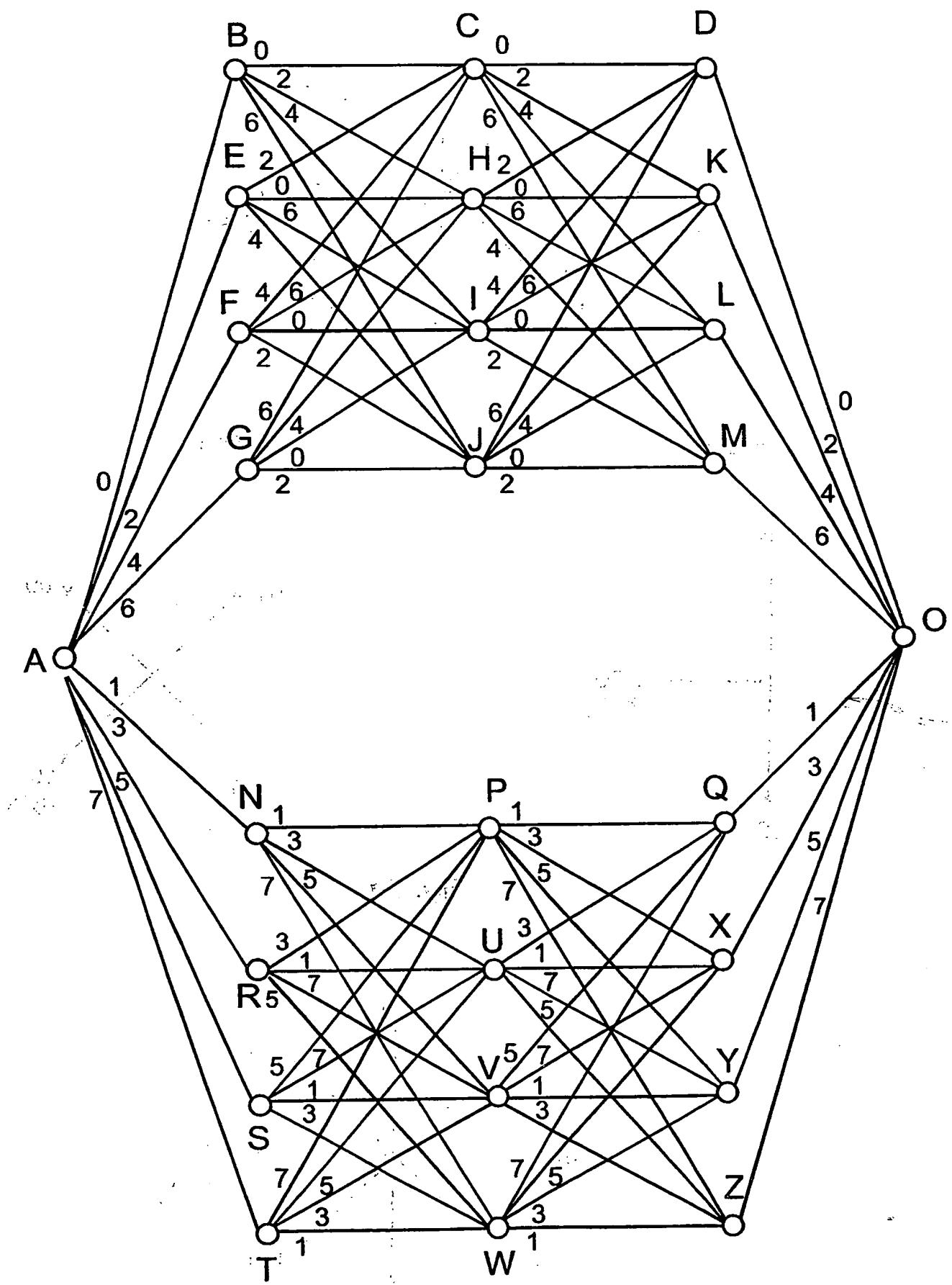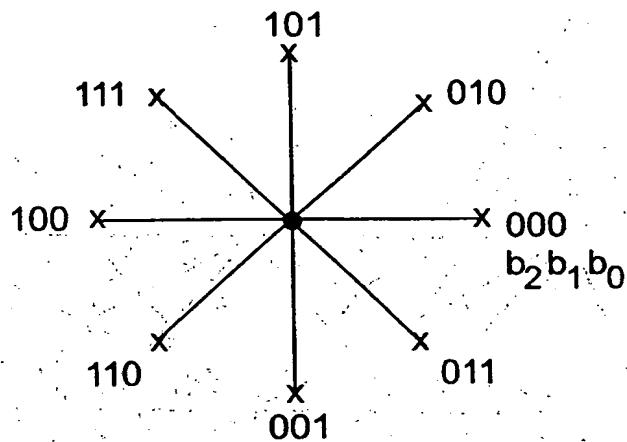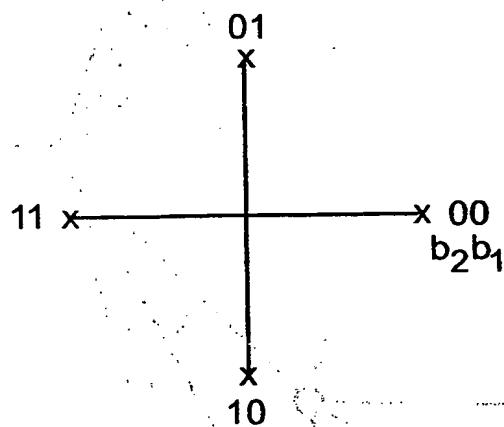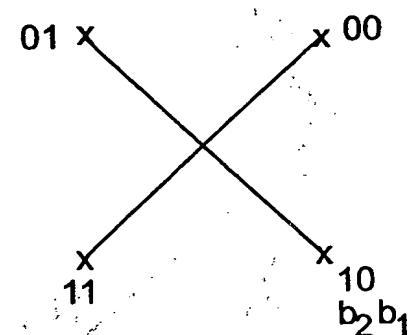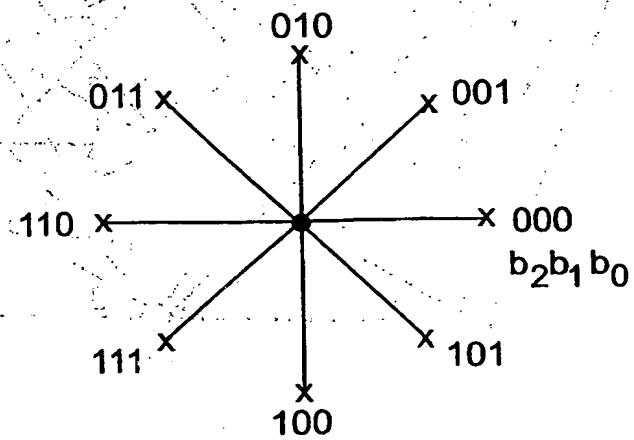
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   H04L27/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category°	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 544 463 A (AT&T) 2 June 1993 cited in the application see column 2, line 24 - line 29 see column 2, line 50 - column 3, line 5 see column 6, line 10 - line 15 see column 7, line 31 - line 37 see column 8, line 30 - line 41 see column 9, line 50 - line 54 see figure 5 ---	1-32
X	EP 0 633 680 A (ERICSSON) 11 January 1995 see page 3, line 30 - line 44 see page 6, line 37 - page 7, line 14 see page 7, line 43 - page 8, line 35 ---	1-12

-/--

[X] Further documents are listed in the continuation of box C.   [X]   Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not
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Date of the actual completion of the international search	Date of mailing of the international search report
22 January 1999	01/02/1999

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category°	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
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X	JIAN LIU ET AL.: "LSB coded 8PSK signals" IEEE TRANSACTIONS ON COMMUNICATIONS, vol. 43, no. 2/4, February 1995, pages 151-153, XP000506542 see figures 2-4 see page 151, left-hand column, paragraph 2 - paragraph 3	13-32

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